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Multi–Objective Aeroelastic Optimization

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1. SUMMARY

The present work is aiming at an aeroelastic analysis of the X31 delta wing and particularly at the aeroelastic optimization problem of maximizing the aerodynamic roll rate and minimizing the structural weight at supersonic flow speeds. Results are achieved by means of a multi–objective genetic algorithm (GA) utilizing a GUI–supported software being developed in the European–Union funded ESPRIT project FRONTIER.

2. INTRODUCTION

In early aircraft design stages, the lifting and control surface sizes, shapes, and positions are determined in order to meet given manoeuver performance requirements. In these manoeuvers, aerodynamic and mass loads are imposed on the structure, creating stresses which the structure must withstand. The structure also yields to these loads, which usually degrades the manoeuvre performance predicted for a rigid aircraft. Therefore, a very stiff structure is desired. In order to meet both the strength and stiffness requirements, material needs to be added, which increases the structural weight. The increase may be prohibitively large, so that a change of the control surface planform is preferred, which, in turn, requires an additional loop of aeroelastic assessments. This trade–off between manoeuvre performance, for example the steady–state roll rate, and weight, both as a function of lifting and control surface configuration, is a common problem of aircraft design.

The work presented in this paper describes methods which visualize the dependency between achievable roll rate and the minimum structural weight required to achieve this performance and withstand the loads in this flight conditions, where parameters related to structural stiffness and control surface shape are used. The goal is to provide a means for selecting the "best" structural and control surface layout for given requirements on performance and weight. To achieve this goal, the minimization of weight and the maximization of performance are formulated as separate objectives in a multi–objective optimization. The following sections describe two levels of aeroelastic analysis used, the optimization framework FRONTIER [1] in which they were embedded, the problem as posed to the framework software, and results.

3. DESIGN EVALUATION SOFTWARE

LAGRANGE [2] is an in–house code of DaimlerChrysler Aerospace AG, Military Aircraft, used for structural analysis and optimization. The code bases on a finite element method and enables consideration of stress, strain, buckling, dynamic, static aeroelastic, and dynamic aeroelastic constraints. Objective function is commonly the structural weight. For static aeroelastic analysis, aerodynamic loads are calculated using linearized aerodynamic influence coefficient matrices for a simple panel method [3]. The constraints in this case are the ratios between aerodynamic loads values on the flexible structure and those on the rigid structure, the so–called "effectivenesses". For example, for ailerons the moment about the aircraft roll axis generated by a specified aileron deflection is decisive. Aileron effectiveness is defined as the moment generated by a wing that is free to deform elastically due to aerodynamic loads, divided by the moment generated by an undeformed wing in the same flow condition.

In the present application, LAGRANGE minimizes the structural weight while maintaining structural integrity in five critical static load cases. Simultaneously, the effectiveness of each aileron is required to exceed a given target value. With the actual aileron effectiveness and wing roll damping values of the minimum weight structure as calculated by LAGRANGE, the achievable roll rate as well as the required aileron deflections are calculated by an additional program. Upper bounds for aileron deflections and hinge moments are considered in this step. In summary, the aeroelastic analysis as described calculates a minimized structural weight and the achievable roll rate for a given aileron split ratio and aileron effectiveness target values. This analysis is referred to in the following as "method A".

Since this first approach is based on very simple, linear aerodynamics, a second aeroelastic analysis was developed which involved higher fidelity aerodynamics. The specific method is the HISSS–D code [4], a higher–order inviscid sub– and supersonic panel method for design which allows iterative and constraint aerodynamic optimization for general three–dimensional flows. HISSS–D may be coupled with LAGRANGE in the system HCSI to perform aeroelastic analysis and optimization. In the approach called "method B" in the following text, HCSI is inserted before the roll rate trim calculation of method A. The system thus uses the structural model as optimized by LAGRANGE with its simple aerodynamics, and re–calculates the actually achieved aileron effectiveness values. In effect, HCSI is used to correct the results of the simple aerodynamic analysis. The trim analysis is performed just as in method A. The following paragraphs describe the details of HCSI.

Aerodynamic and structural analysis are coupled by a procedure which determines the equilibrium of aerodynamic loads and the structural reaction forces. The "structural" relation between load and displacement is commonly assumed to be linear. The "aerodynamic" relation between deflection of the aerodynamic shape and aerodynamic load, however, is not linear. In contrast to widespread practice, this fact is considered in HCSI. As another novel element, analytic sensitivities of the equilibrium loads are determined and provided to the structural optimization.

Paper presented at the RTO AVT Symposium on "Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment", held in Ottawa, Canada, 18-21 October 1999, and published in RTO MP-35.

A major challenge was the (automatic) coupling between the aerodynamic analysis code and the structural method. Flow analysis and structural codes usually use topologically very different meshes. Moreover, "more sophisticated" fluid dynamics analysis methods rely on much finer meshes compared to those used to model the structure. In order to feed the displaced geometry calculated by the structural method back into the flow solver, accurate interpolation in three dimensions must be obtainable. In HCSI, transformations between the meshes are performed using an approach based on statically correct distribution of discrete aerodynamic loads onto a limited set of structural nodes called "beaming". The reverse transformation is used for translating the structural displacements into aerodynamic surface mesh deformations. Conservation of virtual work in the process if these transformations is guaranteed.

The structure of HCSI is displayed in Fig. 1. The transformation functions described above are generated by BEA5. The figure also shows the data flow from the mesh generation system PGRID to HISSS–D and, particularly, the intersection of HISSS–D with CPELA5, LAGRANGE and STRULA. STRULA uses the structural model of LAGRANGE and loads due to unit deflections from CPELA5 to trim the aircraft for a certain target value of, say, steady–state roll rate. The actual trim displacements – and sensitivities with respect to the structural design variables – are then calculated by CPELA5 and returned to LAGRANGE. LAGRANGE performs structural optimization with constraints on stresses resulting from these aeroelastic load cases. In the FRONTIER test case, however, the roll rate is an objective function, that is a *result* of the structural optimization. For this reason only CPELA5 is executed to calculate the aileron efficiencies.

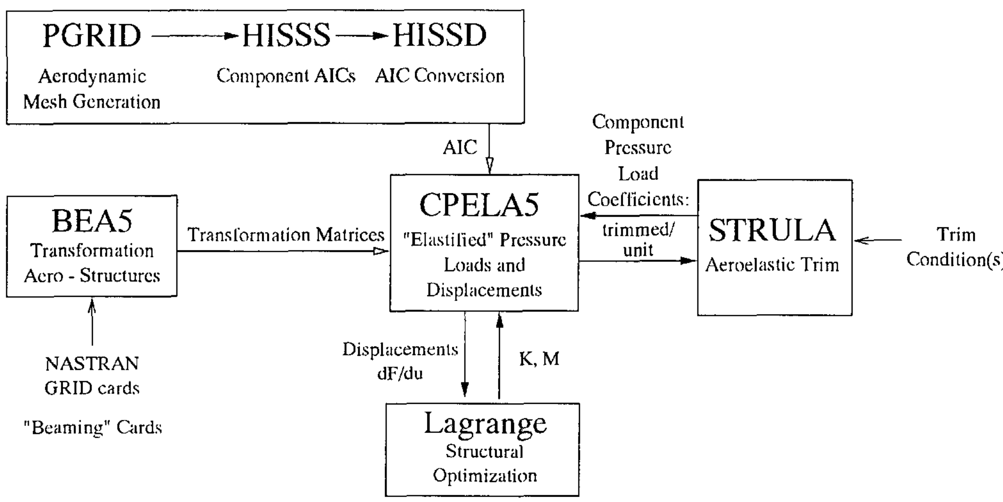

Figure 1 Flow chart of HCSI

4. THE FRONTIER OPTIMIZATION ENVIRONMENT

One of the major results of the European project FRONTIER [1] is an optimization software which can be applied to multi–disciplinary, multi–objective optimization. It employs a genetic algorithm (GA), a "hill climber" (gradient–based optimization algorithm), and a Multi–Criteria–Decision–Making tool, MCDM. A graphical user environment/interface guides the (non–experienced) user. Parallelization of individual generation in the GA cycles is explicitely supported.

The FRONTIER technology is an open system for collaborative design optimization using Pareto Frontiers. The communication between applications on different platforms is enabled by CORBA service calls which provides a high degree of platform independence. The baseline implementation language of FRONTIER is Java [4]. This has proved very advantageous since only one source code is needed for Unix and Windows NT and, moreover, both single and parallel processor platforms are covered.

The multi–objective genetic algorithm (MOGA) for global exploration uses a generational and steady state GA with user–defined number of individuals and generations. A library of selection schemes is available with defaults defined on the basis of performance in mathematical test cases. The operations applied to parents to generate children are crossover and mutation. These are applied to a chromosome encoding of the variables defining the design. Crossover, applied to solutions on or near the Pareto boundary, tends to generate other solutions near the boundary, while mutation tends to create variation in the design set. The user can specify crossover and mutation probabilities – or simply use default values.

Constraints can be handled by objective penalisation with hard and soft constraints or by a supplementary objective. A local hill climber (with constraints) can be used for improvement of GA results but also as a stand–alone tool. The gradient based optimization algorithm used is a BFGS (Broyden–Fletcher–Goldfarb–Shanno) algorithm adapted with modifications for constraint handling. The basic method is a Quasi–Newton method rather than a conjugate gradient method.

The MCDM tool generates a set of utility functions which are selected by the user in the form of pairwise comparisons (judgement) of designs. The total utility is treated as the (weighted) sum of utilities for several criteria (objectives).

The multi–objective–genetic–algorithm (MOGA) optimization provides a Pareto Frontier and, hence, a means to distinguish between results that either fulfill a single objective or results from composite objectives. Moreover, results on the Pareto Frontier can be easily taken as starting points for further engineering evaluations. The FRONTIER optimization technology also allows for hybrid optimization since the gradient based method may be used in order to improve GA results. Of course this latter step is limited to continuous variables, while the GA can manage mixed discrete/continuous design spaces.

5. TRIAL DESCRIPTION

5.1 Two–Level Optimization Procedure

The test case chosen a two–level, two–objective optimization of the composite X31 delta–wing at supersonic flow conditions. The wing model features two leading edge flaps, a wing box, and two trailing edge ailerons, see Figure 2 below. The leading edge flaps are fixed and treated as part of the wing planform. The ailerons may be deflected independently of each other in order to generate a rolling moment.

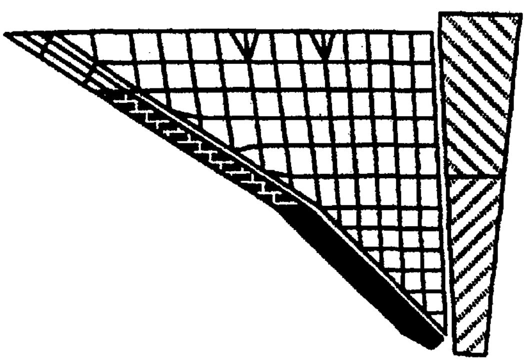

Figure 2 The X31 delta–wing structural model

The objective functions are minimum weight of the wing and maximum achievable roll rate. Three design parameters were used on the FRONTIER framework (upper) level: Roll efficiency goals for inboard and outboard ailerons, and the flap split. The former are continuous parameters, constrained to lie between reasonable bounds. The latter is a discontinous value since rib positioning in the wing box limits possible hinge positions – and thus flap splits – to three discrete values. Hence a coupled set of continuous and discontinuous design parameters had to be treated in a two–objective optimization space. Constraints are not used explicitely on this level.

Figure 3 provides a sketch of the general topology of the upper level design space, where the two efficiencies are combined into one value for the sake of simplicity and presentation. This aileron effectiveness, η, is an indicator of the stiffness of the wing. With increasing stiffness, the achievable roll rate, P, will converge to the value reached by a rigid structure. In order to create a rigid structure, however, it must be infinitely stiff, and therefore infinitely heavy. As a result, as η approaches 1.0, the weight, W, approaches infinity. It is therefore reasonable to provide an upper limit to η. On the other hand, if the effectiveness requirement is very low, the stiffness of the structure necessary to sustain static loads may be suffient to generate efficiencies higher than the requested value. Therefore, one can provide a lower bound to the η–dimension of the design space without changing the outcome. Although qualitatively identical, the quantitative situation depends on the third design parameter, the aileron split ratio, t, which is equivalent to a specific spanwise split position, y_{fl}.

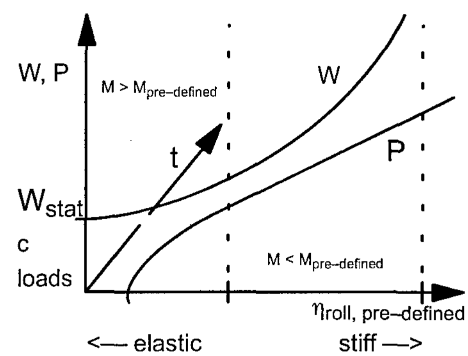

Figure 3 Top level design space topology

In order to receive the minimum weight of the X31 wing, LAGRANGE performs a second type of optimization. Design parameters at this (lower) level are thicknesses and composite fiber orientations of the structural members. These are varied to achieve minimum structural weight while satisfying constraints on allowable stresses and strains, buckling, and aileron roll effectiveness, $\eta \geq \eta_{predefined}$. The latter constraints are the design parameters of the upper level optimization. In the trim calculation, geometric limits are applied to the aileron deflections, $\alpha_{flap,in}$, $\alpha_{flap,out}$, and the hinge moments are limited to values which can be sustained by the actuators installed in the actual aircraft. Thus, while explicit constraints are not set to these parameters at either optimization level, they are implicitely constrained.

5.2 Geometry Parametrization

One of the most crucial items of optimization is reliable parametrization of the geometry. The success and performance of the entire optimization process is closely related to such application–dependent parametrization.

The geometry parametrization of the X31 delta wing is presented in Figure 4. Three design parameters used in the optimization process are highlighted. All other parameters for the complete wing parametrization are kept constant for the current flap efficiency study. It becomes evident from Fig. 4 that the original wing has been extended up to the symmetry plane of the fuselage.

According to the inner layout of the wing structure, Table 1, and based on the limitations that the actuators may not be moved and each aileron requires two hinges, the possible aileron–split domain is bound by the location of the outboard hinge of the inner aileron, and the actuator position of the outer aileron, including a tolerance, ε, for their spanwise dimension:

$$1777 \text{ mm} + \varepsilon < y_{fl} < 2330 \text{ mm} - \varepsilon$$

Three variants were finally selected: variant 1, at the baseline split location, variant 2 at the upper split limit, and variant 3 at the lower bound. These variants are represented by numerical values of the discrete design parameter "aileron split" of 1, 2, and 3, respectively.

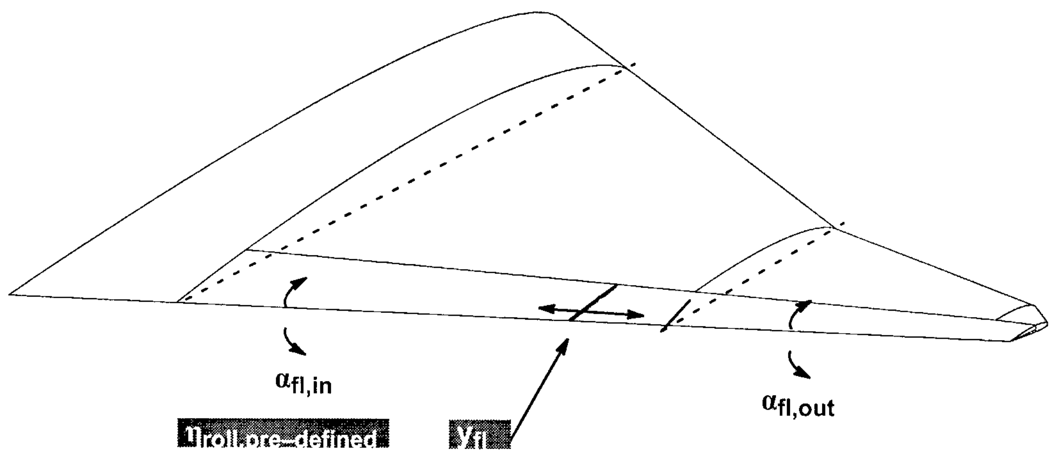

Figure 4 Geometry parametrization

Table 1 Geometry constraints

Geometry item	at position [mm]
Innermost edge of flap	616
Inner rib	783
Hinge with actuator	1046
Hinge	1777
Current yfl–value	2028
Hinge with actuator	2330
Hinge	2845
Hinge	3360
Hinge	3632

5.3 Design and Fixed Parameter Settings

Based on the previous considerations, the design parameters were specified in the FRONTIER environment in the form shown in Table 2. Additional parameters were supplied to the aeroelastic analysis, but not varied:

Mach–number	[–]	= 1.2
Angle–of–attack	[°]	= 5.73
Stagnation_pressure	[N/m**2]	= 102,100
Max. Inb_flap_setting	[deg]	= 15.0
Max. Outb_flap_setting	[deg]	= 15.0
Max. Inb_hinge_moment	[Nm]	= 4500.
Max. Outb_hinge_moment	[Nm]	= 4500.

Table 2 Design parameter settings

Design parameter	Min Value	Max Value	Steps
Aileron Split	1	3	3
Inboard Efficiency	0.2	0.5	151
Outboard Efficiency	0.2	0.5	252

6. RESULTS

6.1 Method A

Based on the values provided in Table 2, optimization was carried out on an SGI ORIGIN–2000 with 16 processors and 8GB shared memory, both as sequential runs and in parallel. The total computation time by using 8 processors 16 generations with 16 individuals each was roughly two hours.

The speedup of the parallel application can be taken from Fig. 5 below. It exhibits a reasonable speedup of about 6 when using 8 processors.

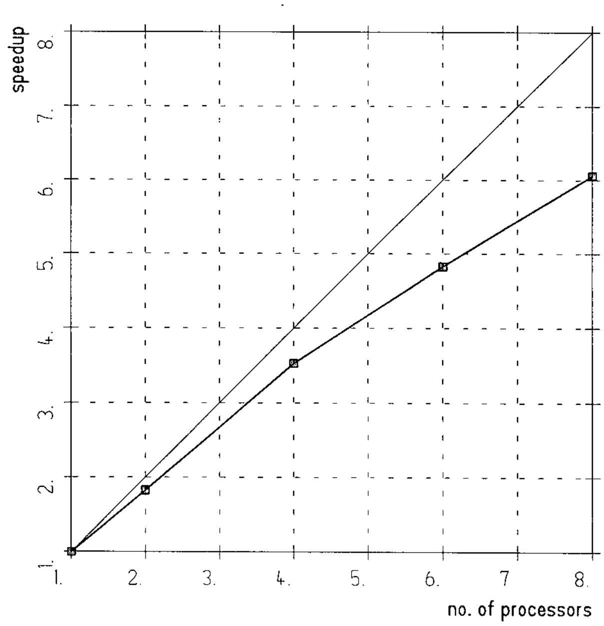

Figure 5 Speedup for parallel treatment of the X31 wing performance trial

It should be noted at this point that – on the basis of 16 individuals per generation – only 2, 4, and 8 concurrent designs might have been the correct choice for the "standard MOGA". However, as for all trials the "steady MOGA" was adopted, the parallel run with 6 concurrent designs denotes an additional – possible – trial.

In Fig. 6, the computed pressure(–coefficient) distribution on the X31 wing surface is shown for the untwisted wing at Ma=1.2, 5.73° incidence, an inboard aileron setting of 20° and an outboard aileron setting of 10°. It very well exhibits the high pressure loads on the aileron which correspondingly lead to the deformations of the aileron, actuator, actuator support, and finally of the wing box.

Optimization results using 16 individuals and 8 generations – utilizing the steady MOGA approach for a total of 128 individuals – are presented in Fig. 7. The simple aeroelastic method A was used to evaluate the individuals.

The corresponding Pareto frontier is presented in Fig. 8. Taking into account an initial weight of about 173N, it becomes evident that there is some room for improving the weight limit, however under the drawback of reduced turning rates.

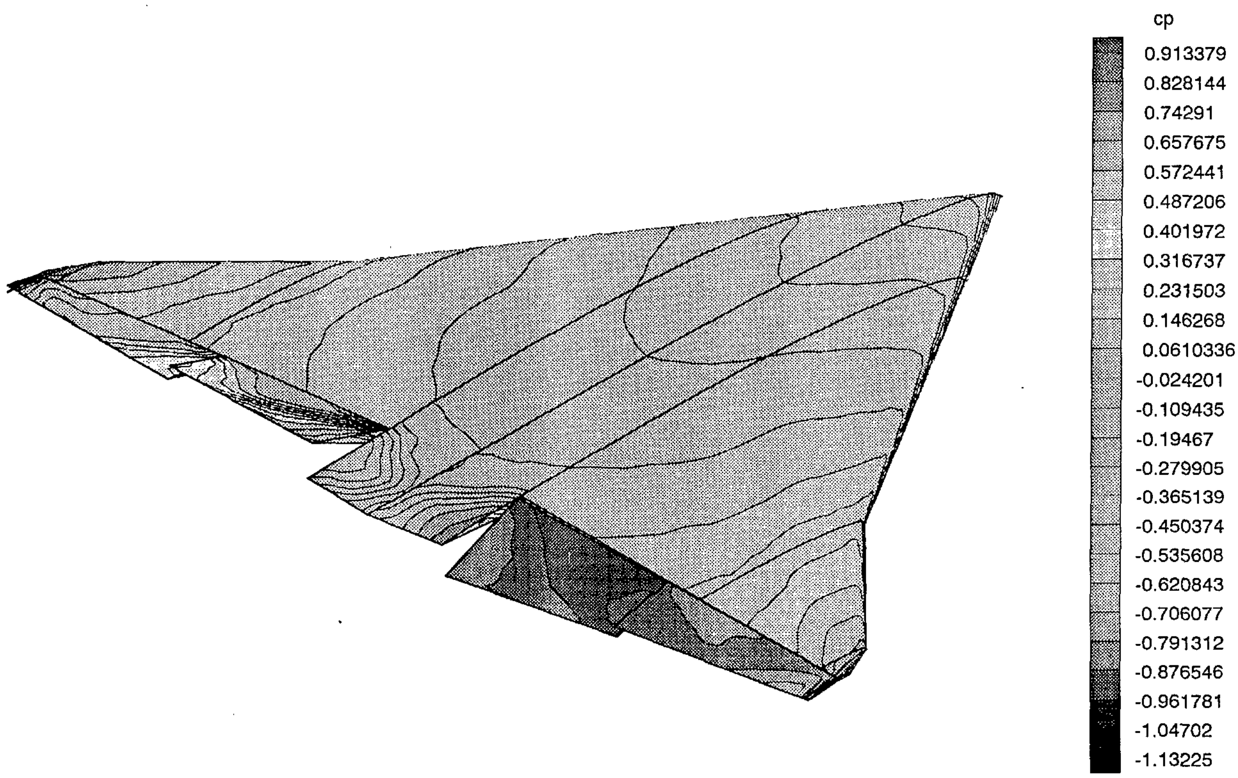

Figure 6 Computational pressure–coefficient results for specific individual

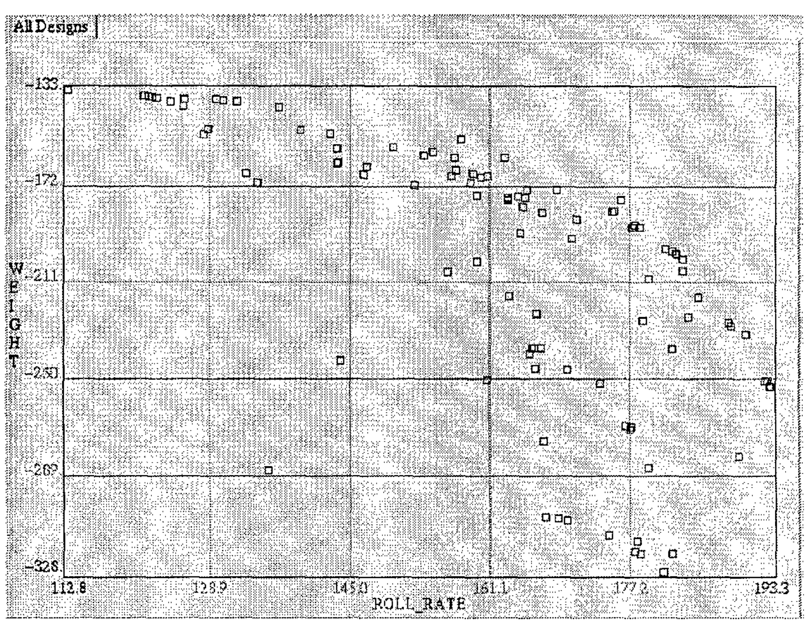

Figure 7 Objective space: Design parameters for 16x8 MOGA run with aeroelastic method A

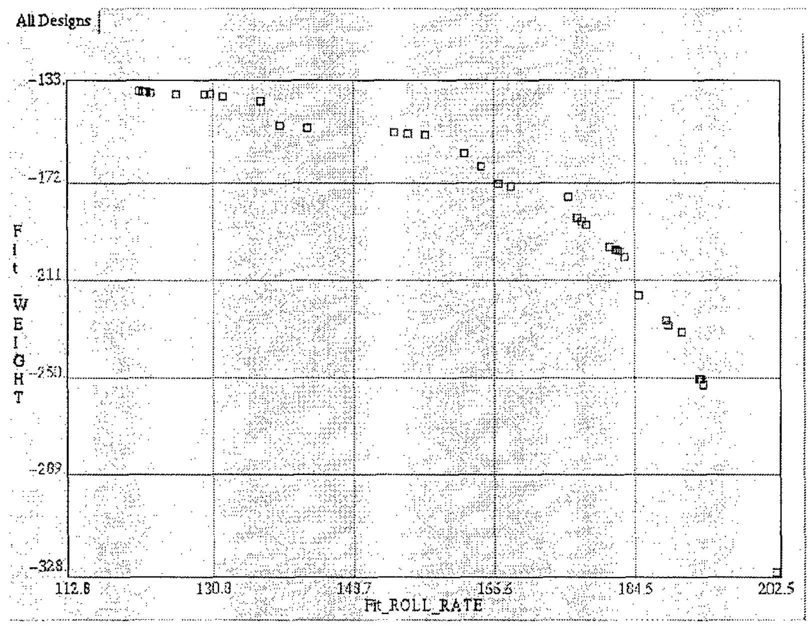

Figure 8 Pareto frontier: Design parameters for 16x8 MOGA run with aeroelastic method A

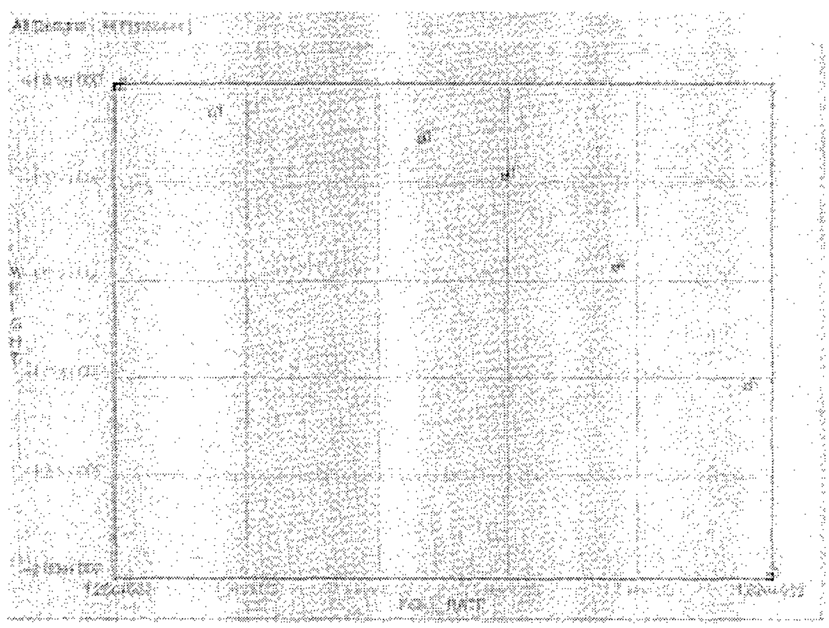

Figure 9 Buffered design for MCDM usage with results selected from to Figure 7 (8)

It should be noted at this point that – although the prescribed numbers of individuals and generations have been fixed in the input file for the FRONTIER run, the "real" number of usable designs differs slightly for the different parallel runs. This is due to the problem that some individuals are non–physical ones and are not taken into account for the design space evaluation. Therefore, the data in Fig. 7 provide the results obtained for the sequential/ non–parallel run.

It was mentioned before that a further improvement of the Pareto results by using a hillclimber is possible but has not been used in the present investigation due to the discontinuous aileron–split design parameter. However, the possibility to fix the aileron's inboard–outboard split by selecting a preferred "best" result from the Pareto frontier and then applying a gradient based method merely with the remaining two design parameters (the flap efficiencies) might be investigated in future trials.

When comparing the different results on the Pareto frontier, it becomes quite evident that the use of a evolutionary strategy – the GA in the current trial – can be efficiently applied to complex test cases. Moreover, for the selected set of design parameters, a gradient based method could have provided results *only* for one flap split, i.e. the present investigation would have been impossible to treat *without* an evolutionary strategy.

The complete set of results further indicate that the roll rate governs the optimization process, i.e. in the low structural–weight area larger improvements of the corresponding roll rate can be obtained – a fact that will be underlined by using the MCDM tool. For the MCDM investigation of the results obtained by method A, Table 3 presents the set of individuals that have been buffered from the Pareto frontier. In addition, Fig. 9 presents the design chosen and their location on the Pareto curve together with the numbering (according to the sequence in the data buffer) used by the MCDM.

It is initially suggested that an experienced engineer would select the same individual from the frontier as a novice user would receive by applying the MCDM method.

Table 3 MCDM trial: Buffered designs

Design no. on Pareto	44	35	49	92	77	90	27
Buffered individual for MCDM	2	1	3	6	4	5	0

In order to rate the different designs given in Table 3, the following set of preferences has been selected for the MCDM run:

5	preferred to	4
2	preferred to	3
7	preferred to	6
6	preferred to	1

The best (priority) result was computed to be individual no. 92, achieving reasonable roll rates together with relatively low structural weight. The two–objective case in that trial is, of course, not a real challenge for the MCDM tool, however it has proven to be in line with the "engineer's nose", i.e. it it suggested that an experienced engineer, properly checking the Pareto frontier, might have chosen a similar result.

Based on prescribed hinge moments of 4500 NM, the design and objective values for individual no. 92 read:

flap split	1	
inboard flap efficiency	0.332	(resulting in $\alpha_{Flap,in}$=3.52°)
outboard flap efficiency	0.3308	(resulting in $\alpha_{Flap,out}$=6.85°)

resulting in

roll rate	159.022 deg/sec
strucural weight of X31 wing	151.668 N

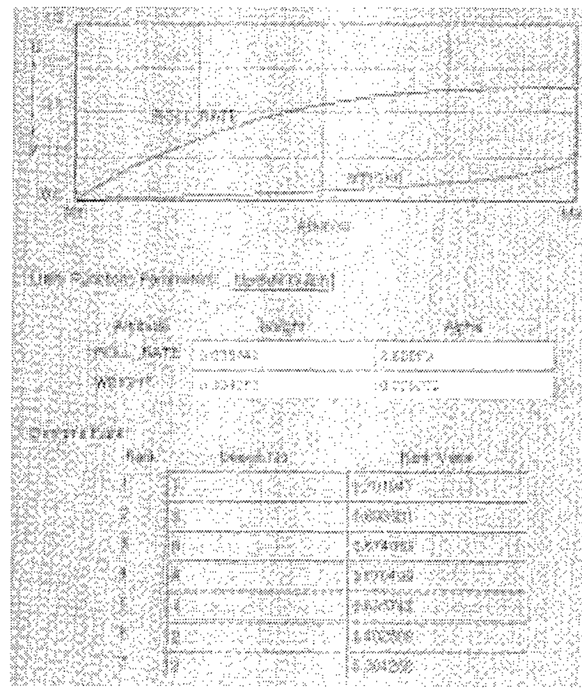

Figure 10 MCDM output

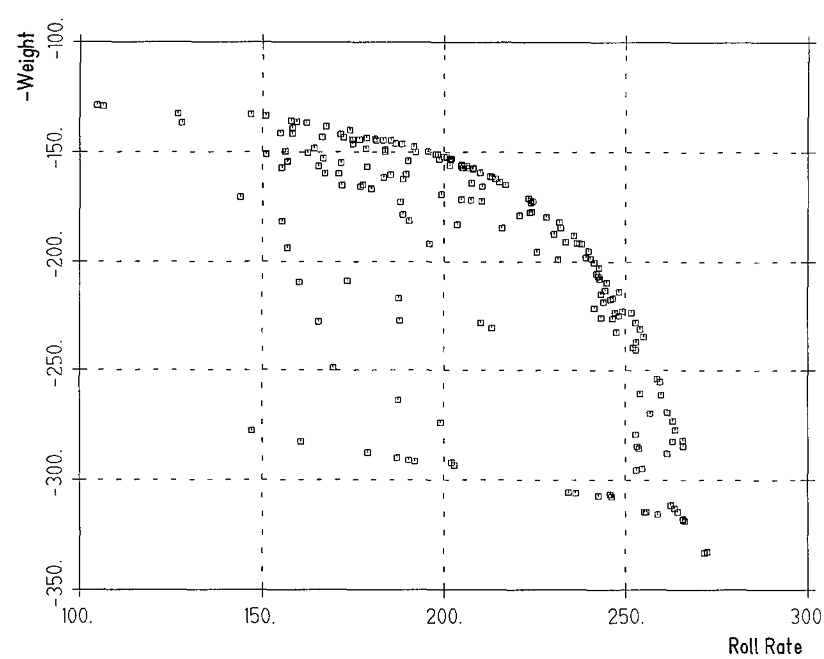

Figure 11 Objective space: Design parameters for 16x16 MOGA run with aeroelastic analysis method B

Fig. 10 presents the MCDM results, indicating the dependencies of roll–rate and structural weight and confirming that the roll rate is dominating the weight. On the other hand, it can be seen for higher weight factors that the roll rate cannot be improved with "although" the structural weight is drastically increasing. In addition, Fig. 10 also provides the obtained rating sequence.

6.2 Method B

Optimization results using 16 individuals and 16 generations – utilizing the steady MOGA approach for a total of 256 individuals – with aeroelastic anaylsis method B are presented in Fig. 11. A rather smooth Pareto frontier – often showing up in "physical", i.e. "non–mathematical", applications – has been obtained.

In comparison to the use of method A, the roll rate obtained by method B has increased by roughly 30%, compare Fig. 7. Checking again against the initial weight of 173 N which corresponds to a roll rate of about 240 deg/sec, the optimization result obtained is very close to flight test results and underlines the maturity of the improved method B in the chosen flight regime.

7. ACKNOWLEDGEMENT

The authors gratefully acknowledge the help by L. Onesti (Parallab Bergen/EnginSoft, Trieste) and A. Turchet (Dasa–M/University Trieste) in setting up the FRONTIER system for the presented test case.

In particular we are grateful to our colleague W. Guldner who coded the approach we termed as method B.

This present work was supported by the European Commission as an ESPRIT (European Strategic Programme for Research and Development in Information Technology) Project, No. 20082.

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